Circulation and hydrography over the Kerguelen Plateau

by

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ABSTRACT. - The Kerguelen Plateau is the largest near-meridional submarine plateau lying across the Antarctic Circumpolar Current (ACC), affecting significantly the large-scale circulation and pathways of the different water masses across the plateau. This has important implication not only for the local primary productivity and marine ecosystem, but also for the meridional overturning circulation of the Southern Ocean. We give here a short review of the circulation and hydrography as well as the ACC transport over and around the Kerguelen Plateau.

RÉSUMÉ. - Circulation et hydrologie sur le plateau de Kerguelen.

Le plateau de Kerguelen est le plus grand plateau sous-marin d'orientation quasi méridienne placé en travers du Courant Circumpolaire Antarctique (CCA), qui affecte de manière significative la circulation à grande échelle et les voies de passage de différentes masses d'eau à travers le plateau. Ceci a des implications importantes non seulement pour la productivité primaire locale et l'écosystème marin mais également pour la circulation méridienne verticale de l'océan Austral. Nous présentons ici un bref aperçu sur la circulation et l'hydrologie ainsi que le transport du CCA sur et autour du plateau de Kerguelen.

Key words. - Kerguelen Plateau - Antarctic Circumpolar Current - Large-scale circulation - Transport - Topographic steering.

The circulation and transport of the Antarctic Circumpolar Current (ACC) typify the fundamental dynamics of the Southern Ocean where diverse water masses originating from different sources of the world's oceans meet and mix while circulating around Antarctica. It is in the Southern Ocean where the Circumpolar Deep Water originating from the North Atlantic Deep Water upwells south of the ACC and then transforms into the Antarctic Bottom Water and Antarctic Intermediate Water, thus completing the southernmost circuit of the global meridional overturning circulation, a key oceanic component of climate. As the largest near-meridional submarine topographic obstacle, the Kerguelen Plateau diverts the ACC over a great distance between the subtropical and subpolar regions. It acts as a natural barrier for closing the eastern boundary of the Weddell Gyre to the west and developing the western boundary of the Australian-Antarctic Gyre to the east of the plateau, thus providing an important meridional pathway for the equatorward evacuation of transformed subpolar water masses.

Despite its indisputable role in the ACC dynamics and the Southern Ocean meridional circulation, the Kerguelen Plateau has long been lacking high-quality oceanographic observations and it is only recently that an increasing multidisciplinary interest from different communities has appeared. For example, the 2005 KEOPS cruise was dedicated to a biogeochemical flux study related to the elevated primary productivity over the northern Kerguelen Plateau (Blain *et al*., 2007) and the 2009 TRACK cruise was designed to measure directly the currents and transport across the Fawn Trough and the Deep Western Boundary Current (DWBC) on the eastern flank of the southern Kerguelen Plateau (Park *et al*., 2009). Recently, there has also been a continuous deployment of animal-borne miniaturized oceanographic sensors by the marine predator ecology community using penguins (Charrassin *et al*., 2004) and elephant seals (Roquet *et al*., 2009).

It is timely to assemble the major achievements from these recent efforts and review the hither-to accumulated key knowledge dispersed in the literature on the circulation and water masses over the Kerguelen Plateau.

The Kerguelen Plateau as a major barrier for the ACC

Circumpolar perspective

Before addressing the detailed regional circulation around the Kerguelen Plateau, it may be instructive to look at the Kerguelen Plateau region from a circumpolar perspective around Antarctica. The ACC can be defined as unobstructed circumnavigating eastward flow passing through the Drake Passage, the geographical distribution of which can be appreciated, for example, from a mean streamline map of baroclinic transport function (Fig. 1A) or a map of altimetry-derived ACC fronts (Fig. 1B). As can be seen from these maps, the ACC is not a purely zonal flow but undergoes great meridional shifts or meanderings especially in the vicinity of deep passages associated with major submarine

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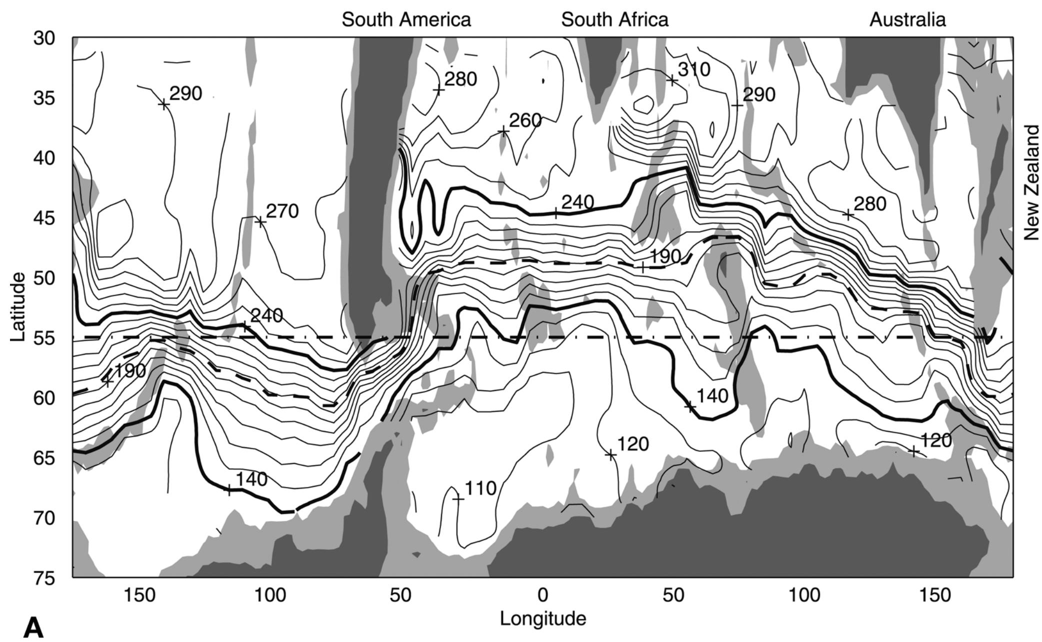

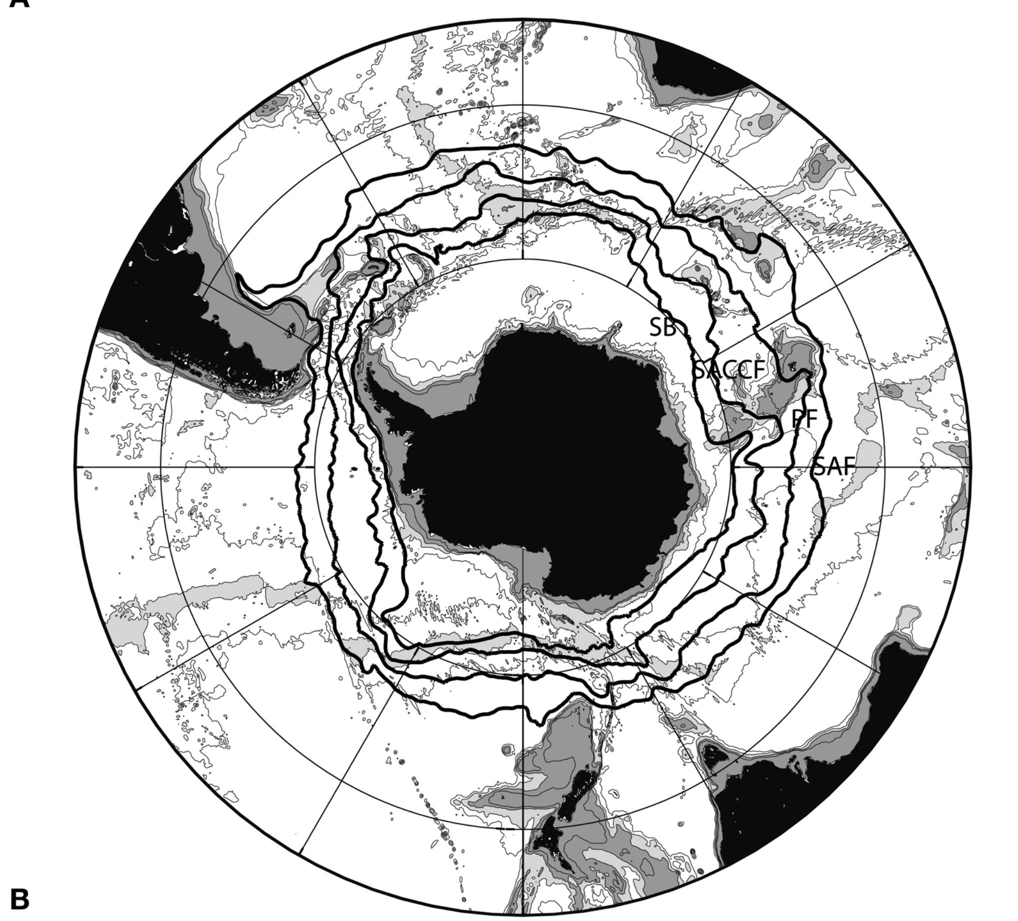

Figure 1. - **A**: Mean streamline map for baroclinic mass transport function, with a contour interval of 10 x 10^3 J m^{-2}. Adapted from Sun and Watts (2002). **B**: Map showing four major Southern Ocean fronts as determined from the altimetry-derived mean dynamic topography of Rio and Hernandez (2004). Adapted from Park *et al*. (2009).

topographic features, such as the regions around the Drake Passage, over the Crozet and Kerguelen Plateaux, south of the Campbell Plateau, and across the Udinsev Fracture zone. Among these, the Drake Passage region shows the most spectacular northward shift of the ACC, with a mean displacement of its southern and northern boundaries attaining

as much as 17° in latitude in the area between the eastern South Pacific and the western South Atlantic. Here, the ACC also spans the most extreme latitudinal extent of about 30° between its southernmost position in the Bellinghausen Sea (69°S, 90°W) and its northernmost position in the Brazil-Malvinas confluence zone (39°S, 55°W).

The ACC in the Atlantic sector of the Southern Ocean is entirely located to the north of the Drake Passage and keeps a nearly zonal course with its northernmost overall position (44°-53°S) until 25°E. Eastward from this longitude, the ACC shows a fan-shaped meridional spreading, with its northernmost branch passing north through the Del Cano-Crozet gap to flow north of the Crozet Plateau at 42°S and then north of the Kerguelen Plateau at 45°S, while its southernmost branch bends far southward by 10° in latitude to reach its southernmost latitude in the Weddell-Enderby Basin at 63°S, just in the upstream area of the southern end of the Kerguelen Plateau. Here, the ACC attains its maximum breadth of about 2000 km (45°-63°S), which is about three times the ACC width through the Drake Passage. This is one of the most apparent characteristics of the barrier effect of the Kerguelen Plateau that forms the largest near-meridional submarine obstacle for the ACC. Downstream from the Kerguelen Plateau, the ACC shows generally a gradual southward shift until the entrance to the Drake Passage, except for a substantial meridional meandering of the southern boundary of the ACC in the Udinsev Fracture region.

The simplest physics behind the large-scale flow meandering across the meridional submarine topographic obstacle is the conservation of potential vorticity f/h, where f is the Coriolis factor and h is the bottom depth for a barotropic flow or the isopycnal layer thickness for a baroclinic flow. To conserve its potential vorticity, the eastward flow over a shallowing topography bends equatorward, while it bends back poleward after crossing the topography. Also, as the deep reaching flow is materially blocked by shallow topography, only sufficiently deep passages offer major throughflow gates to the ACC, which will be detailed below for the Kerguelen Plateau case. The term "topographic steering" is often used to designate the overall qualitative description of flow constrained by topography.

Regional perspective

As remarked by Park and Gambéroni (1997), the simplest way to demonstrate the role of barrier played by the Kerguelen Plateau to the eastward flowing ACC is to show simply a section of bottom topography along the shallowest ridge across the entire width of the ACC, as illustrated in figure 2. This figure clearly shows that the Kerguelen Plateau materially blocks most of the deep-reaching flow, except for three deep passages such as the Kerguelen-Amsterdam passage north of the Kerguelen Plateau, the Fawn Trough dividing the Kerguelen Plateau into two parts, and the Princess Elizabeth Trough between the southern tip of the plateau and Antarctica. The northern Kerguelen Plateau, north of the Fawn Trough, is much shallower than the southern Kerguelen Plateau, especially in the region between the Kerguelen and Heard Islands where the sill depth is less than 650 m. In addition, a shoal much shallower than 200 m is widely developed to the north of the Kerguelen Islands, so that no significant transport of the ACC is expected to overpass it.

The spatial distribution of water properties of the ACC over the Kerguelen Plateau is also constrained by bottom topography and figure 2B presents a temperature section that is close to the topographic section given in figure 2A. Here, the water masses and fronts associated with the ACC spread over a great meridional extent separated by the Kerguelen Plateau, between the Subantarctic Front (SAF) at 45°S and the Southern Boundary (SB) of the ACC at 63°S. The SAF in the frontal zone north of the Kerguelen Islands is tightly merged with the Subtropical Front (STF) and forms the strongest bottom-reaching front of the section, while the SB, which is the southernmost extent of the ACC, can be placed near the northernmost 0°C isotherm intersecting with the bottom topography. The latter is because the ACC crossing the Kerguelen Plateau does not carry bottom water colder than 0°C or the Antarctic Bottom Water (AABW), but the lowest bottom temperature of the ACC rounding the southern tip of the Kerguelen Plateau is 0.1°C according to the source analysis of near bottom silicate data by Donohue *et al.* (1999). To the south of the SB, isotherms tilt strongly upward, suggesting the existence of a significant eastward flow, however, this feature should not be interpreted as associated with the ACC because bottom temperatures there are too low (< 0°C), but it can be best interpreted as the eastward retroflection of the Antarctic Slope Current initially flowing westward to the south of 65°S (not represented in the figure). We will come back to this point later.

Over the Kerguelen Plateau, a unique conspicuous frontal zone is found in the Fawn Trough, a deep passage (< 2800 m) cutting the Kerguelen Plateau into its northern and southern parts. Water characteristics across the frontal zone change dramatically, with a vertical jump in isotherms by 1000 m or more, indicating the presence of a concentrated strong flow called sometimes as the Fawn Trough Current (McCartney and Donohue, 2007; Roquet *et al.*, 2009). It is now well established that the current coincides with the Southern ACC Front (SACCF) according to the circumpolar frontal analysis by Park *et al.* (2009) (see Fig. 1B) using the altimetry-derived surface dynamic topography of Rio and Hernandez (2004), which contrasts with the suggestion of Sparrow *et al.* (1996) who previously interpreted it as the surface expression of the Polar Front (PF). Here, the SACCF is located close to the northern limit of the subsurface temperature minimum (or Winter Water) of 0°C or to the southern limit of the mid-depth temperature maximum (character-

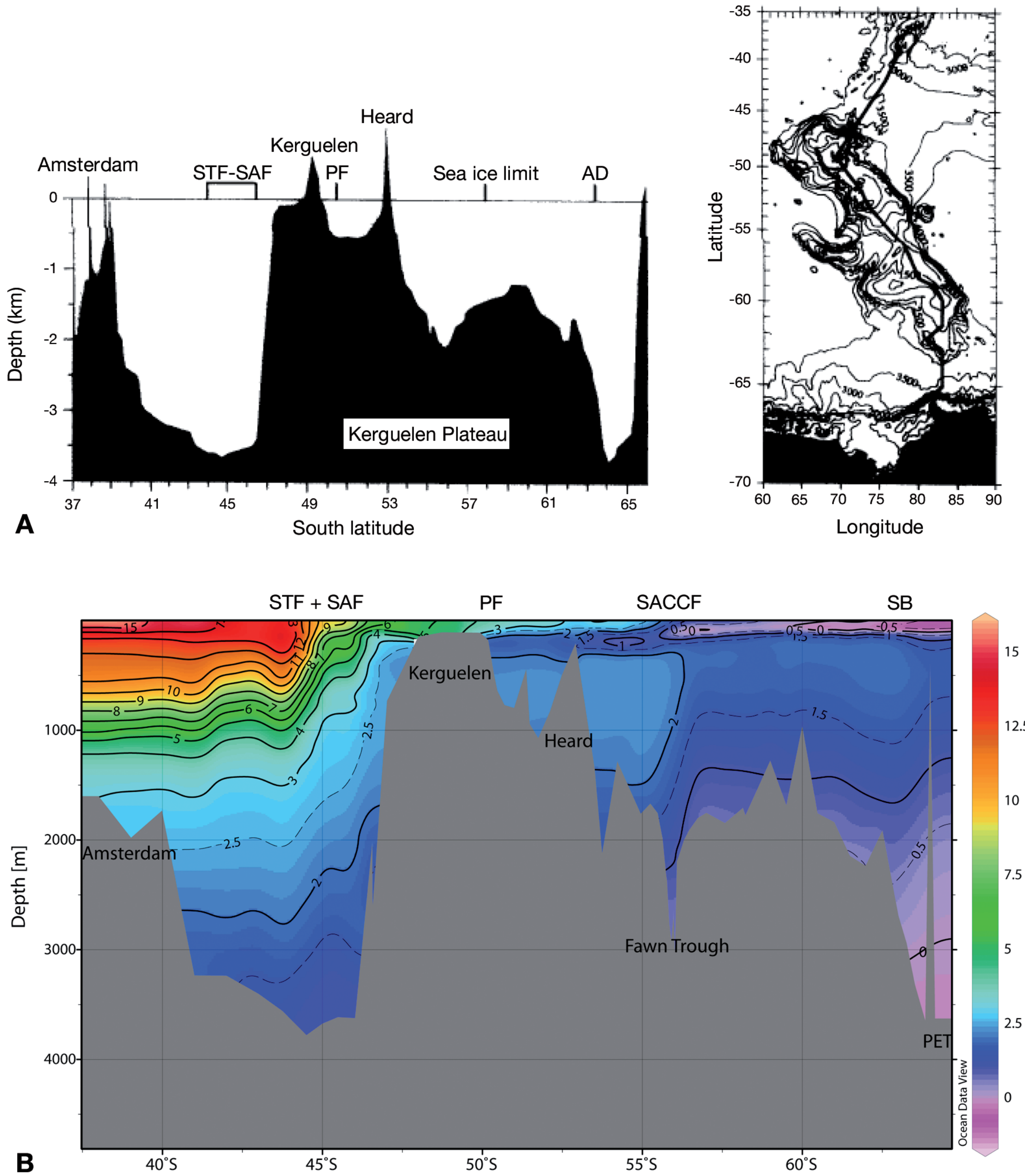

Figure 2. - **A**: Bottom profile between the Amsterdam Island and Antarctica, passing along the shallowest ridge of the Kerguelen Plateau. Adapted from Park and Gambéroni (1997). **B**: Temperature section between the Amsterdam Island and Antarctica along a similar course as (A), constructed from a combined dataset from three previous cruises: SUZIL (Park *et al*., 1993), TRACK (Park *et al*., 2009), and WHP I8S (McCartney and Donohue, 2007).

ising Upper Circumpolar Deep Water) of 2°C.

The PF is defined traditionally as the northernmost extent of Winter Water (or subsurface temperature minimum layer) of temperatures < 2°C. On our near-meridional section of Fig. 2B, the subsurface temperature minimum < 2°C is limited to the south of the Kerguelen Islands and there is no evidence of such a layer to the north of the Kerguelen Plateau. A more detailed discussion on the subject is given below.

Circulation and hydrography over the Kerguelen Plateau

Location of the PF around the Kerguelen Islands

The location of the PF around the Kerguelen Islands has long been debated and great discrepancies exist among different frontal positions suggested in the literature (Roquet *et al*., 2009). For example, Park *et al*. (1993) proposed it

rounding the Kerguelen Islands from the south; Orsi *et al.* (1995) suggested it passing over the shallow shoal north of the Kerguelen Islands; Belkin and Gordon (1996) placed it along the northern flank of the Kerguelen Plateau; Moore *et al.* (1999) put it in the midway between the Kerguelen and Heard Islands. This disagreement among authors is most probably related to the paucity or unavailability of finely resolved synoptic hydrographic sections across the shallow topography around the Kerguelen Islands. However, the most decisive hydrographic dataset for resolving the conflict was gathered from a series of systematic hydrographic surveys made during the 1987-8 SKALP cruises (Duhamel, 1993). Park and Gambéroni (1997) identified unambiguously the PF around the Kerguelen Islands from the SKALP cruise-derived two temperature sections cutting the Kerguelen Plateau in the east-west direction at 49°S and in the north-south direction at 69°E, respectively (Fig. 3). At 69°E, the PF (or the northern limit of Winter Water < 2°C centered at 200 m)

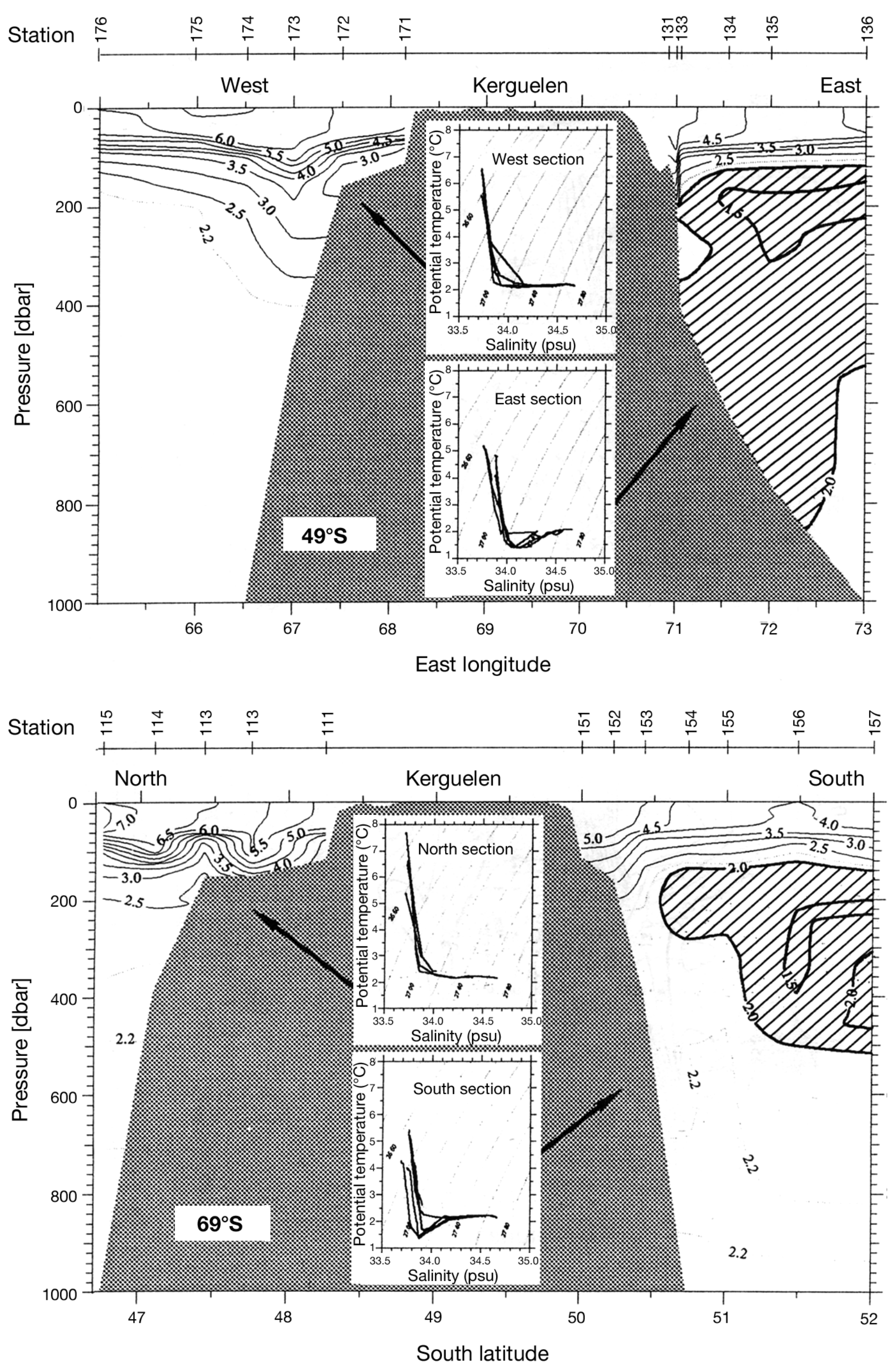

Figure 3. - SKALP cruise-derived zonal (49°S) and meridional (69°E) temperature sections across the Kerguelen Islands, with the subsurface temperature minimum < 2°C being hatched. Also inserted are the temperature-salinity diagrams for four subsections. Adapted from Park and Gambéroni (1997).

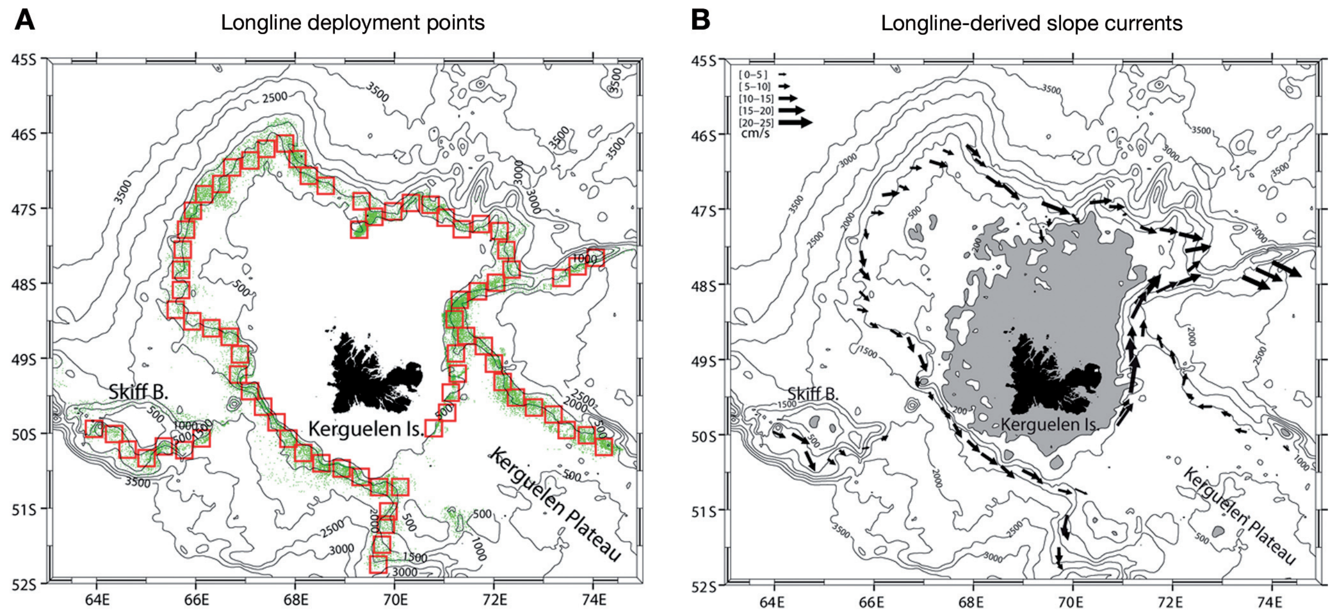

Figure 4. - **A**: Demersal longline deployment points (green dots) for the Kerguelen Patagonian toothfish fisheries for the period 2002-2007. Red rectangles represent the cells where area-averaged longline drifts are computed. **B**: Depth-averaged slope currents around the Kerguelen Islands as estimated from the longline drift data. Adapted from Park *et al*. (2008a).

is found on the southern flank of the Kerguelen Island shoal at 50°35'S, while water over the broad shoal shallower than 200 m is warmer than 2.5°C and no subsurface temperature minimum < 2°C is found in the whole water column over the northern escarpment of the Kerguelen Plateau (see also inserted T-S diagrams). At 49°S, the PF is tightly attached to the eastern flank of the plateau near 71°E, while no Winter Water is found over the western flank of the plateau. All this information clearly indicates that the PF, which demarcates the northernmost extent of the Antarctic Surface Water that is best characterized by the presence of Winter Water, does not flow west and north of the Kerguelen Islands but instead rounds the islands from the south and east. Due to this asymmetric northward shift of the PF along the northeastern flank of the Kerguelen Plateau, the surface layer temperature off the eastern coast of the islands is significantly colder by 1-2°C than its western counterpart.

Slope currents around the Kerguelen Islands

The first quantitative knowledge of the current field around the Kerguelen Islands was obtained from a systematic analysis of fishery observers records from the Kerguelen Patagonian Toothfish (*Dissostichus eleginoides* Smitt 1898) fisheries. Figure 4A shows a total of 28,297 fishing gear setting and recovery positions of demersal longlines deployed between 2002 and 2007 on the continental slope surrounding the Kerguelen Islands. Based on a simple method detailed in Park *et al*. (2008a), it was possible for the first time to draw a realistic chart of slope currents (Fig. 4B), which were computed as time-mean, vertically averaged velocity vectors

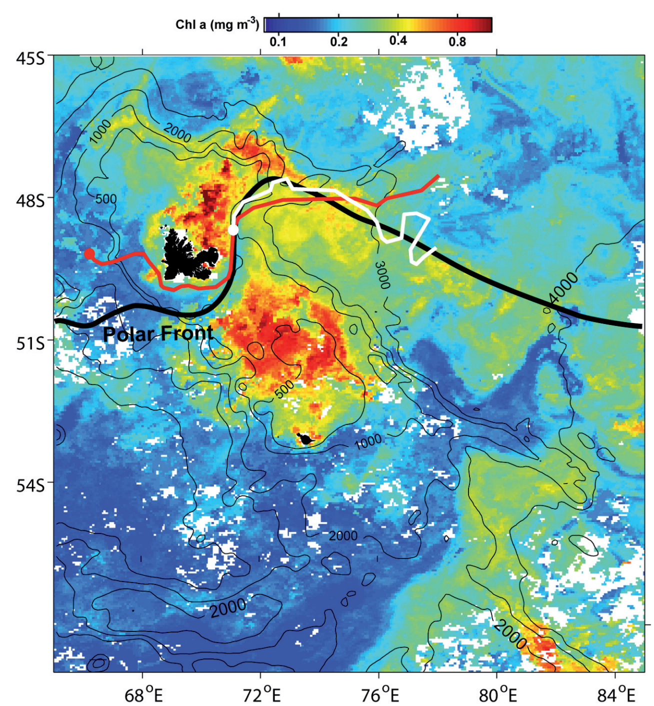

Figure 5. - Chlorophyll concentrations over the Kerguelen Plateau in January 2005, with historic trajectories of two surface buoys and the PF location being superimposed. Adapted from Park *et al*. (2008a).

(over a mean depth of 1000 m between the surface and the bottom). Most vectors are oriented nearly along the bottom topography and adjacent vectors are remarkably coherent

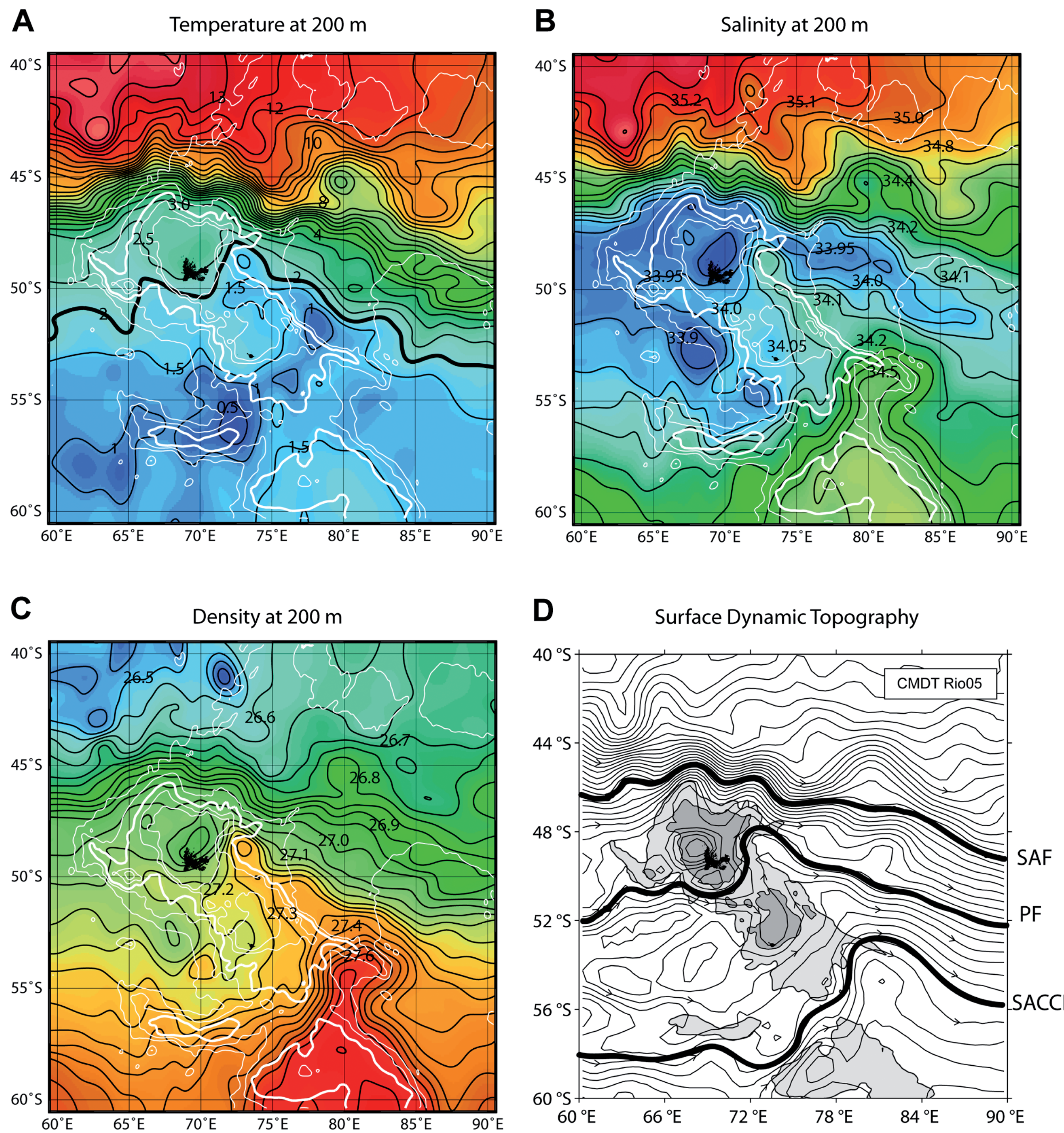

Figure 6. - **A-C**: Property distributions at 200 m, with an isoline interval of 0.5°C for temperature, 0.1 (0.05) for salinities higher (lower) than 34.1, and 0.1 kg m^{-3} for potential density. The 2°C isotherm is marked by a bold line. Bottom depths (white lines) are 500, 1000, 2000 (bold), 3000, and 4000 m. **D**: Mean surface dynamic topography from Rio and Hernandez (2004), with the streamlines corresponding to three ACC fronts being shown thickened. Areas with a bottom depth shallower than 2000 m (500 m) are shown light (dark) shaded. Adapted from Park *et al*. (2008c).

both in magnitude and direction, indicating that the method works well. Consistent with the hydrographic evidence noted above, the strongest northward flow attaining up to 25 cm s^{-1} (in depth-mean velocity) hugs the eastern flank of the Kerguelen Island shoal, before retroflecting southeastward from 48°S, 72°E. On the other hand, the slope currents west of the islands are directed to the south (not north), which is also consistent with the previous remark that the PF does not flow west and north of the islands but rather rounds the islands from the south and east.

Further supporting, and probably more visually appealing, evidence for the PF location has been provided by historic trajectories of surface buoys superimposed on a map of surface chlorophyll concentrations (Fig. 5). The band of low-chlorophyll concentrations, originating from the unproductive upstream region west of the plateau and extending to the south and east of the Kerguelen Islands, is a recurrent feature which appears every austral summer. This feature has often been used as the clearest surface marker of the PF of the area (Charrassin *et al*., 2004; Park *et al*., 2008a, 2008c). We see also a downstream chlorophyll plume extending southeastward from the northeastern corner of the Kerguelen Plateau, which is in good agreement both with buoy trajectories and the PF location. The presence of a swift flow like the PF immediately south and east of the Kerguelen Islands has important implications for maintaining two well-separated sources of chlorophyll of the region: one on the shallow shoal north of the Kerguelen Islands and the other over the platform between the Kerguelen and Heard Islands. These two sources of primary production in turn have dual implications for sustaining the regional living resources and their predators as well as for regulating oceanic CO_2 uptake.

Property distributions and circulation over the northern Kerguelen Plateau

As already mentioned, the Antarctic Zone south of the PF is best characterized by the presence of Winter Water that is generally found at about 200 m over the northern Kerguelen Plateau north of the Fawn Trough, across which the Winter Water core layer climbs sharply to less than 100 m to the south of the SACCF. Therefore, it may be instructive to examine property distributions at 200 m (Fig. 6A-C) to obtain useful information on the upper-layer circulation as well as the pathway of Winter Water over the northern Kerguelen Plateau.

The SAF and SACCF act as two principal ACC fronts in the Kerguelen Plateau area by their pronounced across-front property gradients, especially in salinity and density. According to Park *et al*. (1993), the respective ranges of temperature and salinity at 200 m across the SAF in the Crozet Basin are 4-8°C and 34.1-34.5, which can be distinguished from those of the STF, namely: 8-12°C and 34.6-35.0. These two fronts are very closely located to each other or merged into a single structure around 45-46°S until 76°E, downstream of which they begin to separate completely due to an abrupt northward bend of the STF and a gradual southward shift of the SAF.

The SACCF in the Fawn Trough region is associated with a pronounced gradient of salinity and potential density at 200 m, with an across-front range of 34.2-34.5 and 27.4-27.6 kg m^{-3} respectively; there is no significant gradient in temperature at this depth. The front initially runs along the southern flank of the Elan Bank at 58°S before bending sharply northward from 72°E to pass through the Fawn Trough. It is completely separated from the SAF by a distance of about 1400 km in the west of the Kerguelen Plateau, but they approach much more closely to each other (by a factor of two) in the east of the Kerguelen Plateau, just at the outlet of the Fawn Trough.

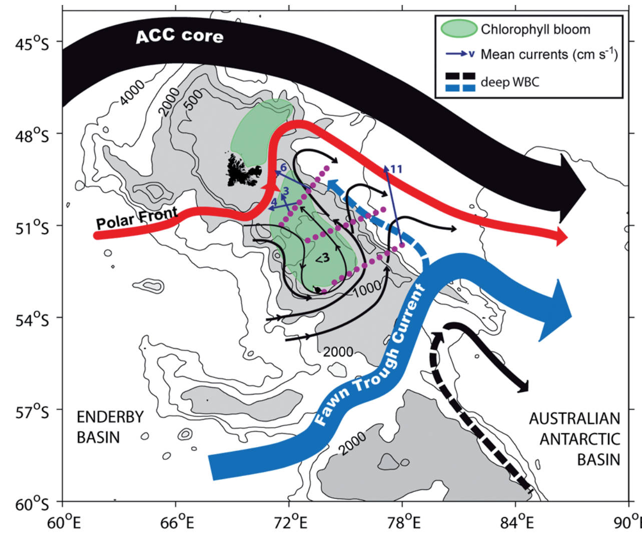

Figure 7. - Schematic of the large-scale circulation around the northern Kerguelen Plateau, with thin arrows with Arabic numerals standing for directly measured upper-layer velocities during the KEOPS cruise. Adapted from Park *et al*. (2008c).

The PF is marked by a bold line on the 2°C isotherm, although it is not associated with a significant property gradient especially in the upstream area west of the Kerguelen Islands. However, in the downstream area east of the islands we observe a moderate but distinctive gradient around the 2°C isotherm, the 34.05 isohaline, and the 27.2 kg m^{-3} isopycnal. This zonal asymmetry of the PF's property gradients relative to the Kerguelen Islands is related to the northwestward extension along the eastern flank of the plateau of relatively cold (< 1.5°C), saline (> 34.05) and dense (> 27.2 kg m^{-3}) water originating from the south of the Heard Island.

The altimetry-derived surface circulation (Fig. 6D) is remarkably coherent with the property distributions, except for the DWBC region along the eastern flank of the southern Kerguelen Plateau southeast of the Fawn Trough. Both altimetry and hydrography fail to depict the northwestwardly flowing strong DWBC that has been clearly evident in direct observations (McCartney and Donohue, 2007; Aoki *et al*., 2008; Park *et al*., 2009).

Based on the synthesis of various observational data (KEOPS and historic hydrographic data, trajectories of surface drifters and mid-depth floats, altimetry-derived surface dynamic heights), Park *et al*. (2008c) presented a schematic of the upper-layer circulation over and around the Kerguelen Plateau (Fig. 7). This figure emphasizes a strong topographic steering of different branches of the ACC crossing the pla-

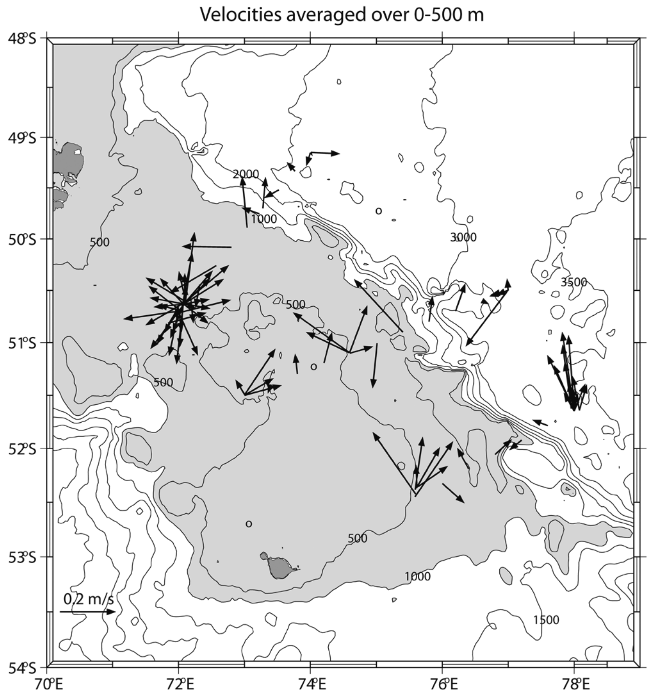

Figure 8. - Instantaneous depth-mean velocity vectors averaged over the upper 500 m layer at KEOPS stations where velocity profiles were obtained via a lowered acoustic Doppler current meter (LADCP). Some stations were repeated several times and station A3 (westernmost station) was occupied for 36 h with repeated LADCP castings at intervals of about 2 h. In this map time-varying, anticlockwise rotating tidal currents are dominant and the maximum velocity shown is about 20 cm s^{-1}.

teau. The circulation over the shallow platform between the PF and SACCF (Fawn Trough Current) is quite weak (3-5 cm s^{-1}) and anticyclonic, with the branch in the eastern side of the Heard Island shoal flowing consistently northwestward to meet in the east of the Kerguelen Islands the PF rounding the islands from the south. In this sense, the former branch coming from the south of Heard Island can be assigned as the southern branch of the PF. It is remarkable to see that the local primary production over the platform is mostly confined within this weak anticyclonic circulation system, a unique feature over the northern Kerguelen Plateau.

Sokolov and Rintoul (2009) recently proposed multiple jets associated with major circumpolar fronts; however, it is worth emphasizing that our circulation scheme over the northern Kerguelen Plateau is completely different from that of these authors who placed their three branches of the PF rounding the plateau along the 2000 m isobath. Consequently, the Sokolov and Rintoul's frontal scheme prohibits any circumpolar flow from crossing the northern Kerguelen Plateau shallower than 2000 m that spans about 1000 km from 47°S to 56°S, which is not supported by our synthesis of different observational datasets.

Internal tides and vertical eddy diffusivity

According to direct current measurements during the KEOPS cruise (Park *et al*., 2008b, 2008c), while the general circulation is quite weak (<5 cm s^{-1}), the instantaneous currents over the platform of the northern Kerguelen Plateau are dominated by much stronger (15-20 cm s^{-1}) tidal currents rotating in an anticlockwise direction (Fig. 8). The magnitude of tidal currents decreases with bottom depth, so they become quite weak (3-5 cm s^{-1}) in deep offshore areas. In addition, inertial currents (period ~15 h at 52°S), which have a comparable spectral energy to tidal currents, are ubiquitous in current meter mooring data, indicating that tides and

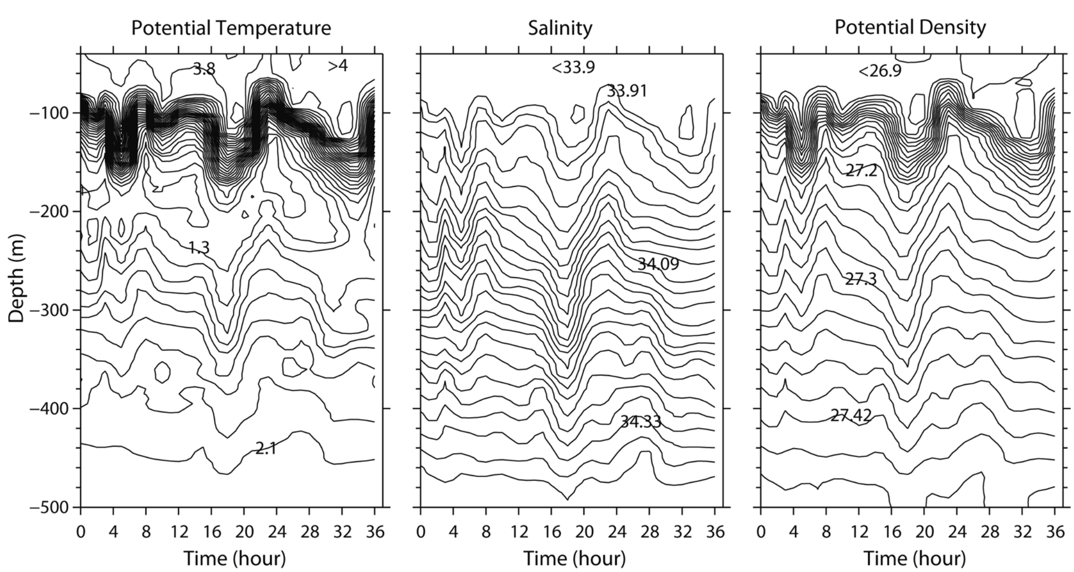

Figure 9. - Time-depth diagrams of potential temperature, salinity, and potential density at KEOPS station A3. Isolines are every 0.1°C, 0.02, and 0.02 kg m^{-3}, respectively. Adapted from Park *et al*. (2008b).

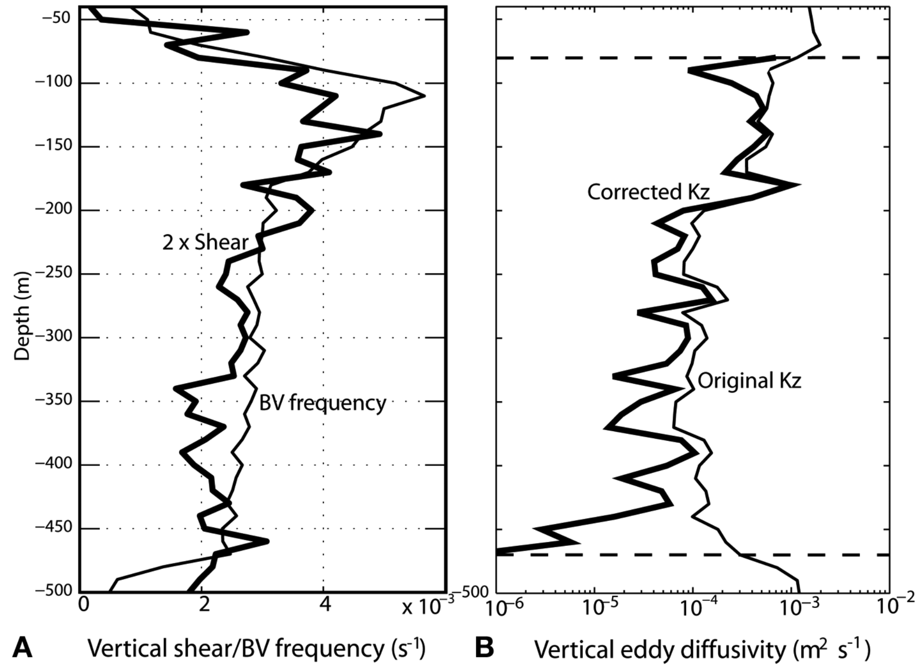

Figure 10. - **A**: Mean profiles of vertical shear (thick line) and Brunt-Väisälä frequency (thin line) at KEOPS station A3. **B**: Mean profile of validated vertical eddy diffusivity (thick line) as compared to the original uncorrected estimates (thin line). Adapted from Park *et al*. (2008b).

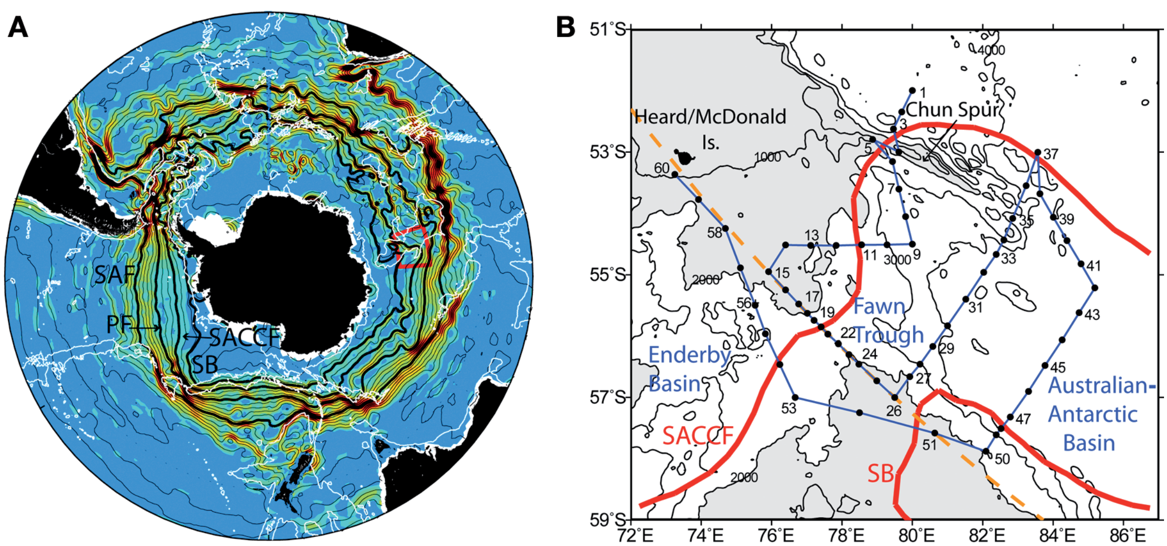

Figure 11. - **A**: Surface streamlines from the mean dynamic height of Rio and Hernandez (2004), with bold streamlines standing for four circumpolar fronts and colour shading representing the relative strength of surface geostrophic currents. The 3000 m isobath (white) and the TRACK cruise area (red) are also indicated. **B**: TRACK cruise map showing the grid of 60 CTD stations, with two southernmost circumpolar fronts being superimposed. A dotted line is the Jason altimeter ground track #94. Isobaths are every 1000 m and bottom depths < 2000 m are shaded. Adapted from Park *et al*. (2009).

winds form two dominant forcing agents for high-frequency fluctuations of the Southern Ocean.

The interaction of tidal currents with the sloping bottom of the plateau generates internal tides, and figure 9 shows the internal tides observed at the time series station A3 during the KEOPS cruise. Peak-to-peak displacements of property isolines reach up to 80 m in the seasonal pycnocline (80-200 m), with their amplitude decreasing with depth. First vertical mode semidiurnal waves are dominant, although they are much distorted by superposed higher frequency and higher vertical mode waves, yielding highly nonlinear internal tides.

Internal tides eventually cascade into turbulence, thereby sustaining enhanced vertical mixing within the water column, which promotes the upward transfer of bottom-enriched iron that is the major limiting factor for the primary production in the Southern Ocean. This hypothesis was test-

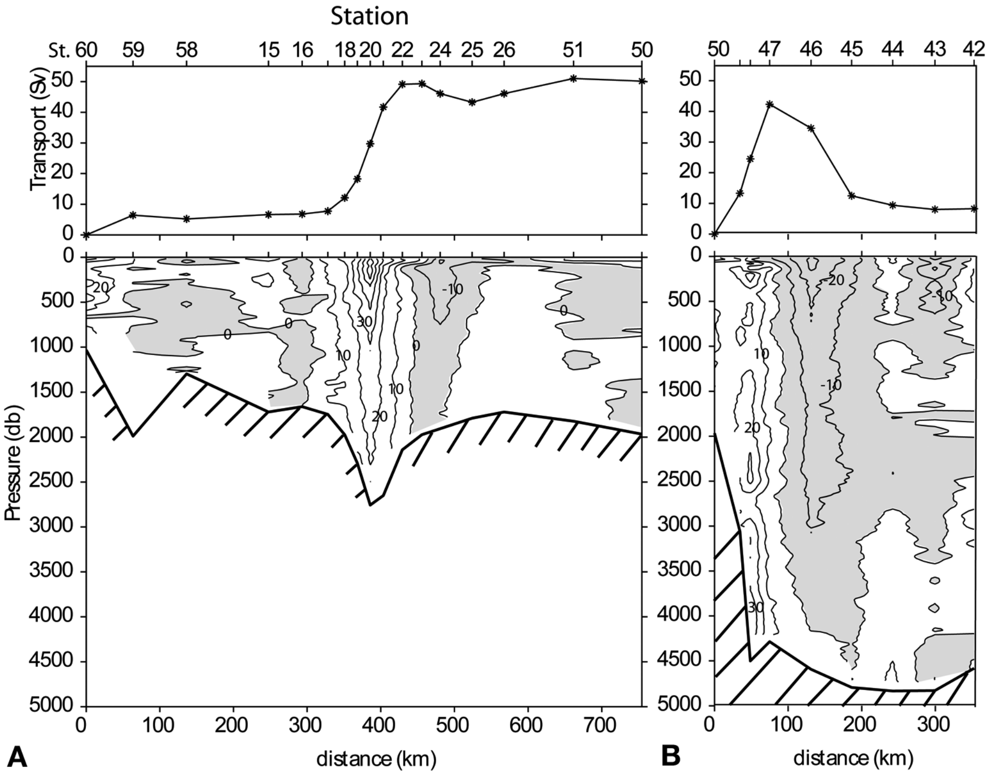

Figure 12. - Vertical profiles of cross-track LADCP velocities and cumulative top-to-bottom transport in the (**A**) western (Fawn Trough) and (**B**) southern (DWBC) sections. Adapted from Park *et al*. (2009).

ed during the KEOPS cruise by computing the vertical eddy diffusivity using different methods (Park *et al*., 2008b), and figure 10B shows the results using the Thorpe scale analysis. Vertical eddy diffusivities of the order of 4 x 10^{-4} m^2 s^{-1} are estimated in the seasonal thermocline below the surface mixed layer, which are an order of magnitude greater than the canonical value (10^{-5} m^2 s^{-1}) in the open ocean away from boundaries. Shallow submarine topographic features stand out as the most plausible sources of iron to the intermediate layers of the water column at station A3, where this nutrient may be advected horizontally by the weak anticyclonic mean circulation whilst diffusing vertically toward the surface mixed layer. These results suggest the importance of the joint action of advection by a sluggish mean circulation and intense turbulent vertical mixing due to internal tides for sustaining the spatially heterogeneous primary productivity over the Kerguelen Plateau.

ACC transport across the Kerguelen Plateau and concluding remarks

Until recently, no systematic high-quality observations had been made over the Kerguelen Plateau, especially across the Fawn Trough. Previous knowledge of major branches of the ACC and associated transports between the Kerguelen Islands and Antarctica was largely indirect and debated, with transport estimates ranging from 30 to 100 Sv (Park *et al*., 1991; Sparrow *et al*., 1996; McCartney and Donohue, 2007). In February-March 2009 closely-spaced, full-depth hydrographic and direct current measurements in the Fawn Trough area were made during the TRACK (Transport across the Kerguelen Plateau) cruise on R/V *Marion Dufresne II*, as part of a French contribution to the International Polar Year activities. This cruise occupied in particular a near-meridional section across the Fawn Trough and repeated the western boundary segment of the WOCE (World Ocean Circulation Experiment) I8S section at 58°S (Fig. 11). Three lines of current meter mooring with a total of 12 current meters were maintained for about 1 year across the SACCF, which were recovered in January 2010 during the TRACK recovery cruise. The preliminary results from the 2009 TRACK cruise (Park *et al*., 2009) are summarised below, while the velocity time series data from recovered current meters are under analysis as part of a thesis program.

Vertical profiles of cross-track LADCP velocities and corresponding transport across the western (SACCF) and southern (DWBC) sections are shown in figure 12. In the western section (Fig. 12A) most of the eastward flow is tightly concentrated in the Fawn Trough, with the strongest flow of 0.6 m s^{-1} at the surface decreasing to 0.3 m s^{-1} at 1000 m, below which the velocity is nearly constant reaching > 0.2 m s^{-1} at 2000 m, indicating that both the baroclinic and barotropic components of current are equally important. A secondary eastward flow branch with a depth-averaged velocity on the order of 0.2 m s^{-1} is observed on the near-shore slope just south of the Heard and McDonald Islands. The net transport across this 750 km-long western section

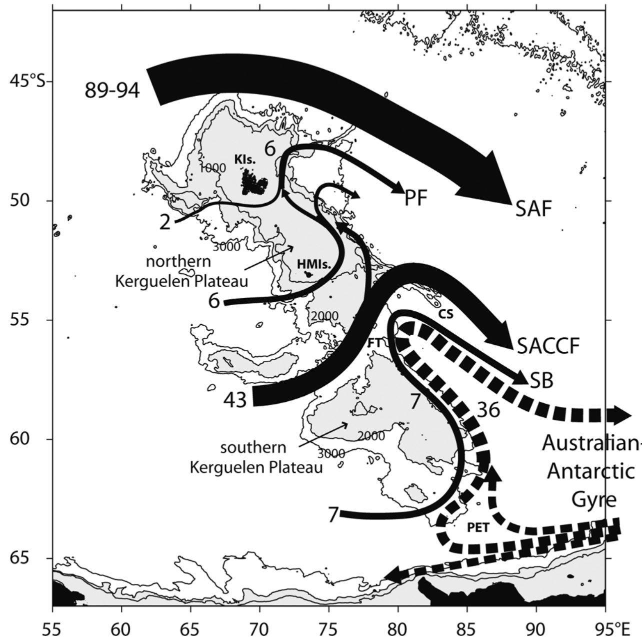

Figure 13. - Schematic of major pathways and transports (in Sv) of the ACC system (bold continuous lines) and DWBC of the Australian-Antarctic Gyre (bold discontinuous lines). Adapted from Park *et al*. (2009).

amounts to 50 Sv (1 Sv = 10^6 m^3 s^{-1}) northeastward, 43 Sv of which are concentrated at the SACCF and 6 Sv immediately south of the Heard and McDonald Islands. In the southern section (Fig. 12b) the northwestward flowing DWBC is highly barotropic and mostly confined within a narrow (~75 km) continental slope. It is also characterized by a bottom-intensified flow, with the highest velocity >0.3 m s^{-1} being found at the bottom at station 48. The total transport of the DWBC amounts to 43 Sv, which is largely compensated by a poleward recirculation transport of 34 Sv in the offshore area.

The TRACK cruise has permitted us to evaluate for the first time reliable transport values of different ACC branches crossing the Kerguelen Plateau (Fig. 13). Including ~2 Sv inferred at the PF south of the Kerguelen Islands, the net ACC transport to the south of the islands amounts to 58 Sv: 43 Sv at the SACCF passing through the Fawn Trough; 6 Sv south of the Heard and McDonald Islands; 7 Sv at the SB through the northern Princess Elizabeth Trough. The latter 7 Sv was obtained by considering only those stations in the southern section where the bottom water has a temperature > 0.1°C containing relatively high silicate (McCartney and Donohue, 2007), while the major component (36 Sv) of the DWBC with a bottom temperature < 0.1°C should be fed by the northward turning of the (low silicate) Antarctic Slope Current along the western limb of the cyclonic subpolar gyre. The rest of the Antarctic Slope Current continues to the west. The schematic of Figure 13 shows in the northern Princess Elizabeth Trough east of 80°E the eastward retroflexion of the Antarctic Slope Current before its northwestward turning to feed the DWBC, a feature well supported by a number of iceberg trajectories (Aoki *et al*., 2010).

According to Park *et al*. (1993), the ACC main branch associated with the SAF should carry 89-94 Sv out of the total 95-100 Sv estimated to the north of the Kerguelen Islands, because ~6 Sv is attributed to the northward flowing PF just east of the islands. These transports estimated to both the north and south of the PF sum up to 147-152 Sv as the total ACC transport in the Kerguelen area, which are not significantly different from the 147 ± 10 Sv at 140°E (Rintoul and Sokolov, 2001). These ACC transport estimates in the Indian sector of the Southern Ocean are consistent with the Drake Passage transport of 137 ± 8 Sv (Cunningham *et al*., 2003) augmented by 10-15 Sv of the Indonesian Throughflow.

Finally, the Kerguelen Plateau blocks the inter-basin exchange of Antarctic Bottom Water, forming two well-separated abyssal gyres on each side of the plateau: the Weddell Gyre to the west and the Australian-Antarctic Gyre to the east. The eastern flank of the southern Kerguelen Plateau supports the western limb of the latter gyre and acts as a deep western boundary permitting the equatorward evacuation of the Antarctic Bottom Water of Adélie Land and Ross Sea sources. In the subsurface layer, the coldest Winter Water (< -0.5°C) originating from the subpolar Enderby Basin is funnelled northward into the Fawn Trough before continuing its northward travel along the eastern flank of the northern Kerguelen Plateau (Park *et al*., 2009; Roquet *et al*., 2009). In summary, although the Kerguelen Plateau appears as a prominent topographic barrier for the ACC, its topographic steering favours the northward evacuation of subpolar waters in both abyssal and subsurface layers, thus efficiently contributing to the meridional overturning circulation of the Southern Ocean.

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